

Intracluster Medium through three years of WMAP

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Abstract

Wilkinson Microwave Anisotropy Probe (WMAP) has provided us with the highest resolution all-sky maps of the Cosmic Microwave Background. As a result of thermal Sunyaev-Zel'dovich effect, clusters of galaxies are imprinted as tiny, poorly resolved dips on top of primary CMB anisotropies in these maps. Here, I describe different efforts to extract the physics of Intracluster Medium (ICM) from the sea of primary CMB, through combining WMAP with low-redshift galaxy or X-ray cluster surveys. This finally culminates at a mean (universal) ICM pressure profile, which is for the first time directly constrained from WMAP 3yr maps, and leads to interesting constraints on the ICM baryonic budget.

Key words: cosmology, cosmic microwave background, methods: data analysis, intergalactic medium

1 Introduction

Since the discovery of dark matter by Zwicky in 1937 (1), which was done through study of virial velocities of galaxies in clusters, galaxy clusters have been in the forefront of cosmological studies.

One of the most promising tracers of galaxy clusters is the thermal Sunyaev-Zel'dovich (SZ) effect, induced in the Cosmic Microwave Background (CMB) sky through scattering of CMB photons off hot electrons in the Intracluster Medium (ICM) (2). Most significant properties of SZ effect as a tracer of clusters can be summarized as (3):

- It is proportional to the line of sight integral of the ICM pressure.

- It has a characteristic frequency dependent signature which enables observers to extract it from the CMB background.
- The total SZ flux of a cluster does not depend on redshift for $z \gtrsim 1$, making SZ effect an ideal tool for making high redshift cluster surveys.

In contrast to free-free X-ray emission, which traces the square of electron density, the fact that SZ effect follows gas pressure makes it a more representative tracer of gas density, and less sensitive to small scale structure or astrophysical processes (e.g. (4)). Therefore, it is believed that SZ flux can be used as a reliable tracer of cluster mass with relatively low scatter.

This has motivated many SZ cluster surveys, which are expected to give a census of dark matter halo mass function at high redshifts, and thus enable novel constraints on the expansion history of the Universe (5).

However, despite theoretical expectations, it is not quite clear how well SZ observations can be calibrated to trace dark matter halo properties. Therefore, complementary X-ray and SZ observations, as well numerical studies are necessary to obtain a realistic picture of the ICM properties.

In this note, I outline efforts to extract the SZ effect from the highest resolution all-sky maps of CMB produced by Wilkinson Microwave Anisotropy Probe (WMAP) (6; 7), the resulting constraints on ICM pressure profile, and comparison with other X-ray and SZ observations, as well as numerical studies.

2 Optimal SZ detection in cross-correlation

While SZ observations of a limited number of massive clusters are existent in the literature (10; 11), due to their limited resolution and sensitivity, they have only been used to put constraints on over-all SZ flux (or gas mass) in conjunction with X-ray observations. Although WMAP has a worse resolution than the instruments commonly used to carry out SZ observations, it covers the whole sky, and thus includes SZ signatures of all the galaxy clusters in the Universe (see Fig. 1). Therefore, although the WMAP SZ signals of individual clusters have a low significance, it is possible to combine SZ signatures of many clusters to obtain constraints on the mean ICM properties.

First efforts in this direction have been made through direct cross-correlation of galaxy/cluster surveys with the WMAP temperature maps (6; 13; 14; 15; 12). In particular, (12) finds an almost 4σ detection of the thermal SZ effect through analysis of 2MASSxWMAP cross-power spectrum (Fig. 2). While these results were generally consistent with theoretical expectations, the observable signal contains a mixture of information, including non-linear galaxy

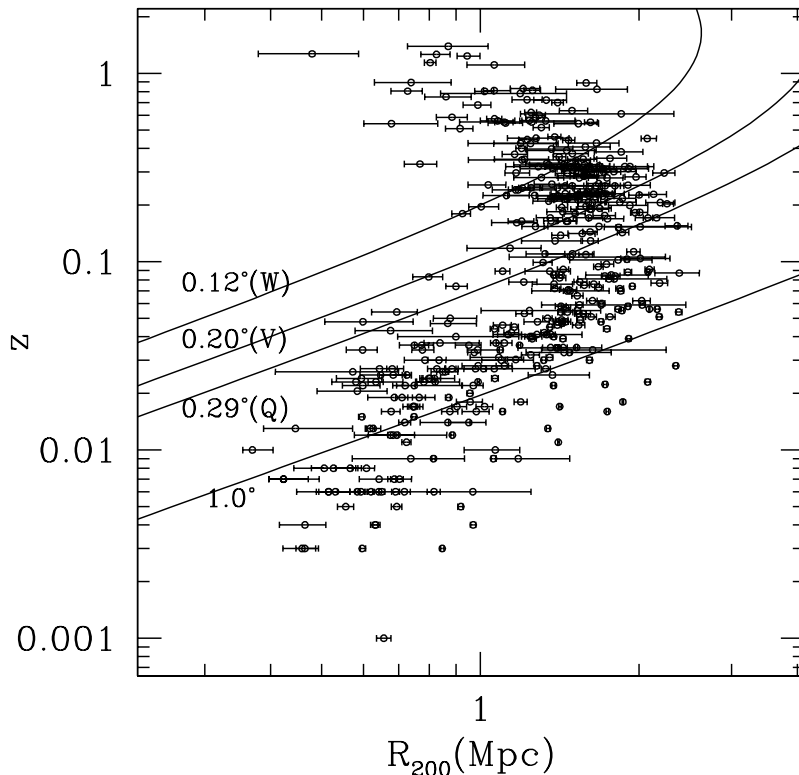


Fig. 1. Estimated virial radii, R_{200} , for all clusters with measured X-ray temperatures in the literature (8), plotted against their redshift. The lines show the physical sizes of the effective angular radii of WMAP beams, as well as a degree angular scale, as a function of redshift in a Λ CDM cosmology. Many low-redshift clusters are in fact resolved by WMAP (9).

bias, halo clustering, and ICM physics. Moreover, the non-Gaussian/non-linear nature of the SZ signal implies that a simple cross-power spectrum analysis is not the optimum way to unleash its full statistical significance. This became clear following the analysis of (16; 17) who could find $S/N \sim 5$ for their SZ detection, through cross-correlating with a non-linear template made out of different galaxy surveys. Despite its better statistical significance, the disadvantage of the latter method was that the galaxy biasing was mixed with ICM physics in a yet more complicated way, making comparison with theory even less certain (but see (18)).

Is there an optimum way to extract the SZ signal of a low-resolution CMB map, using a survey of the low redshift universe, without mixing ICM physics and non-linear clustering information? Although there have been many studies of the correlation of optical properties of clusters with their dark matter halo properties, such correlations have been far from perfect. On the other hand, the temperature of the ICM diffuse X-ray emission has been shown to be a far

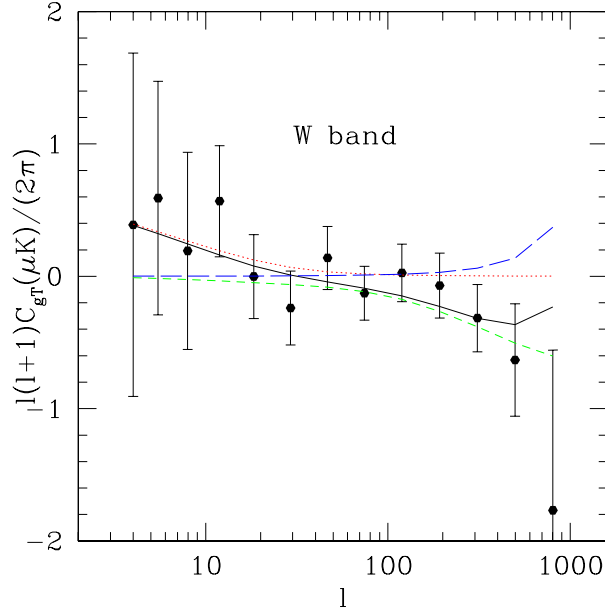


Fig. 2. The cross-power spectrum of 2MASS XSC galaxies in the magnitude bin $13.5 < K_{20} < 14$, with the 1st yr WMAP W-band (12). The red (dotted), blue (long-dashed), and green (short-dashed) lines correspond to best fit Integrated Sachs-Wolfe, radio point source, and thermal SZ contributions respectively. The marginalized significance of the thermal SZ signal (4 2MASS magnitude bins \times 3 WMAP frequency bands) is 3.7σ .

better tracer of halo intrinsic properties¹ (e.g. see (19), and references therein).

This motivated our study of WMAP 1st year data (9), where we constrained a mean (universal) model for ICM, assuming that all the ICM properties have a minimal scaling with the observed X-ray temperature of galaxy clusters. The universal ICM model in (9) assumes a polytropic ICM which is in hydrostatic equilibrium within a dark matter NFW potential (20), and is truncated by an accretion shock at the virial radius. This only leaves the total ICM gas mass fraction (or f_{gas}) as the normalization of the expected SZ signal, which we can fit for as a function of T_X , by looking at WMAP maps within the neighborhood of a compilation 116 X-ray clusters (Fig. 3). After marginalizing over possible point source contamination, this leads to an 8σ detection of SZ effect.

¹ One may worry about the cyclic nature of this statement, as different physical properties (such as virial mass, gas mass, and X-ray temperature) are derived from the same X-ray observations.

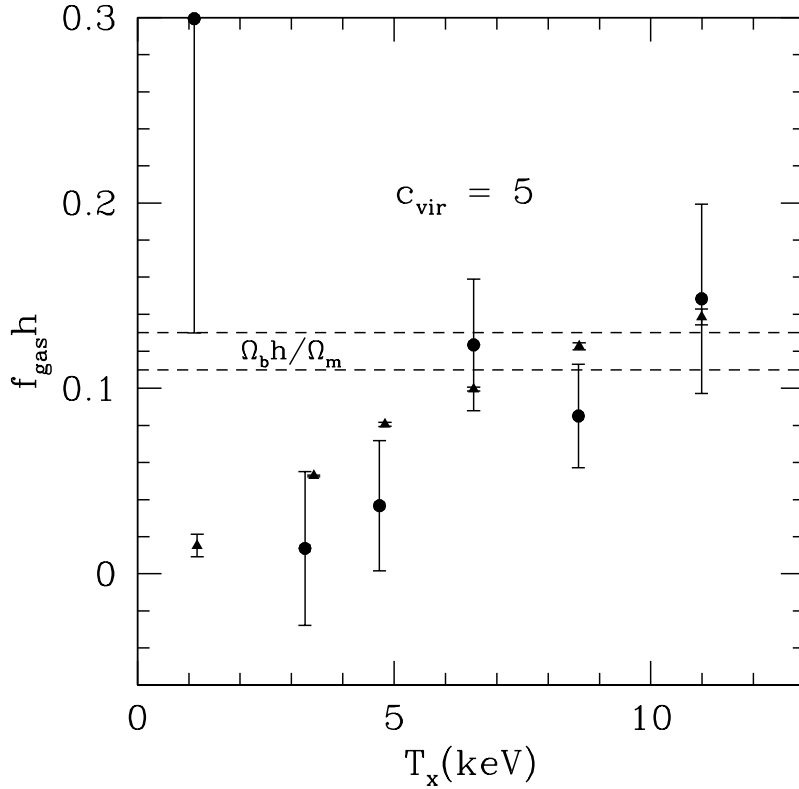


Fig. 3. The inferred ICM gas mass fraction times h (Hubble constant in units of 100 km/s/Mpc), averaged within 2 keV T_x -bins (9). The solid dots correspond to WMAP 1st yr SZ signal, while triangles are gas fractions inferred from cluster X-ray luminosities. The dark matter halo is assumed to have an NFW profile (20) with $c_{\text{vir}} = 5$, and the dotted lines show the cosmic baryonic budget.

3 Reconstructing the ICM mean pressure profile

Due to their limited dynamical range, none of the SZ observations of galaxy clusters have so far been able to significantly constrain the ICM pressure profile. As a result, the interpretation of SZ observations have always relied on profiles that are either directly observed in X-rays (e.g. (11; 10)), or are motivated by X-ray observations (e.g. our analysis of (9), discussed above). As pointed out by (11; 21), this could potentially lead to systematic discrepancies, especially if X-ray and SZ observations probe different parts of the ICM profile (e.g. (22)). Moreover, as X-ray emission is a non-linear function of gas density, any inference of a gas density/pressure profile is model-dependent and is thus prone to systematic biases.

Given the large dynamical range of WMAP resolution, and the high S/N achieved in our earlier analysis (9), it is conceivable that one could construct an ICM pressure profile by effectively stacking all the clusters that are resolved

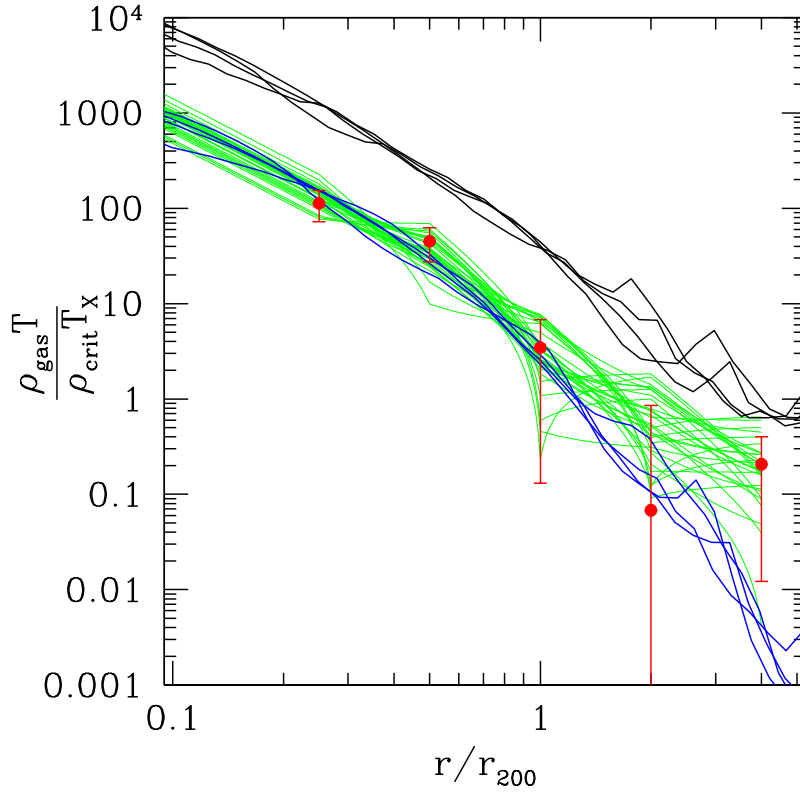


Fig. 4. The mean pressure profile of 109 of our most massive clusters with $T_X > 5$ keV (red points+errorbars); (8). The green curves are 30 random realizations of the measured points, which reflect the errors, as well as their correlations. The blue curves are predicted pressure profiles from four simulated clusters with $T_X > 5$ keV (25; 26), while black curves show dark matter density from the same simulations, divided by the critical density of the Universe, ρ_{crit} .

by WMAP. Following this line of thought, in (8), we devise a method to constrain the full mean (or universal) ICM pressure profile using the newly released WMAP 3yr CMB maps. The only remaining theoretical assumption in this approach is that the physical size of the ICM profile scales as $T_X^{1/2}$, which is consistent with numerical simulations (23) and high resolution X-ray observations (24).

Fig. (4) shows the mean pressure profile for our most massive clusters, with $T_X > 5$ keV, after we exclude clusters with significant point source contamination. We see that the reconstructed pressure profile (red points/green curves) are in excellent agreement with realistic hydrodynamic simulations (25; 26), in the same temperature range.

4 Are we missing cluster baryons?

One of the most surprising findings of recent SZ observations (e.g. (10), and references therein) which is confirmed by our WMAP SZ observations at larger scales (9; 8) is that about 30 – 40% of cluster baryonic budget is missing from the Intracluster Medium. In fact, WMAP maps are the first to have enough dynamical range to show that these baryons cannot be present within the virial radius of ICM. Similar results are also seen in recent X-ray observations (27; 24), while hydrodynamic simulations contain a similar gas fraction in the form of cold gas (26).

On the other hand, stellar mass of cluster galaxies only seems to account for 10 – 15% of cluster baryonic budget (28), leaving about 15 – 30% of the cluster baryonic budget (at $2 - 3\sigma$ level) un-accounted for. There does not seem to be a conventional solution to this new dilemma of the ICM physics (8).

5 Conclusions and Outlook

As the era of the next generation of CMB experiments is fast approaching, it is vital to understand the kind of signals that these experiments are expected to see, the most significant of which is the thermal SZ effect. Moreover, the SZ effect is believed to be the most efficient and robust way of detecting clusters at high redshifts, which can be used to constrain the history of dark energy in that era. To what extent these promises can be realized is the subject of on-going research and inquiry.

In this note, we argued that despite its low resolution, WMAP, as the highest resolution existing all-sky CMB map, can bring in a unique perspective into the understanding of cluster SZ properties, and ICM physics in general. However, this information can only be extracted through combination with a tracer of low redshift universe, such as galaxy surveys or X-ray cluster observations. We described different methods to exploit this SZ signal, which involve varying degrees of theoretical modeling. In particular, WMAP provides the only available observations of the ICM outskirts, and thus for the first time constrain the cluster total SZ flux (or thermal energy).

Both X-ray and SZ observations of the ICM are prone to systematics and technological limitations that could complicate or confuse their interpretation. While on-going theoretical/numerical studies go a long way in understanding these systematics, it would not be the first time that nature outdid the Astronomers' imagination. Therefore, complementary cluster observations (and surveys) in SZ, X-rays, and gravitational lensing (along with numerical stud-

ies) is the only guaranteed way to obtain a comprehensive picture of the ICM physics, and thus be able to reliably use them as a *Dark Energy machine*.

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